



Advanced Radioisotope Power Conversion Technology Research and Development

Wayne A. Wong
Glenn Research Center, Cleveland, Ohio

The NASA STI Program Office . . . in Profile

Since its founding, NASA has been dedicated to the advancement of aeronautics and space science. The NASA Scientific and Technical Information (STI) Program Office plays a key part in helping NASA maintain this important role.

The NASA STI Program Office is operated by Langley Research Center, the Lead Center for NASA's scientific and technical information. The NASA STI Program Office provides access to the NASA STI Database, the largest collection of aeronautical and space science STI in the world. The Program Office is also NASA's institutional mechanism for disseminating the results of its research and development activities. These results are published by NASA in the NASA STI Report Series, which includes the following report types:

- **TECHNICAL PUBLICATION.** Reports of completed research or a major significant phase of research that present the results of NASA programs and include extensive data or theoretical analysis. Includes compilations of significant scientific and technical data and information deemed to be of continuing reference value. NASA's counterpart of peer-reviewed formal professional papers but has less stringent limitations on manuscript length and extent of graphic presentations.
- **TECHNICAL MEMORANDUM.** Scientific and technical findings that are preliminary or of specialized interest, e.g., quick release reports, working papers, and bibliographies that contain minimal annotation. Does not contain extensive analysis.
- **CONTRACTOR REPORT.** Scientific and technical findings by NASA-sponsored contractors and grantees.

- **CONFERENCE PUBLICATION.** Collected papers from scientific and technical conferences, symposia, seminars, or other meetings sponsored or cosponsored by NASA.
- **SPECIAL PUBLICATION.** Scientific, technical, or historical information from NASA programs, projects, and missions, often concerned with subjects having substantial public interest.
- **TECHNICAL TRANSLATION.** English-language translations of foreign scientific and technical material pertinent to NASA's mission.

Specialized services that complement the STI Program Office's diverse offerings include creating custom thesauri, building customized databases, organizing and publishing research results . . . even providing videos.

For more information about the NASA STI Program Office, see the following:

- Access the NASA STI Program Home Page at <http://www.sti.nasa.gov>
- E-mail your question via the Internet to help@sti.nasa.gov
- Fax your question to the NASA Access Help Desk at 301-621-0134
- Telephone the NASA Access Help Desk at 301-621-0390
- Write to:
NASA Access Help Desk
NASA Center for Aerospace Information
7121 Standard Drive
Hanover, MD 21076



Advanced Radioisotope Power Conversion Technology Research and Development

Wayne A. Wong
Glenn Research Center, Cleveland, Ohio

Prepared for the
Second International Energy Conversion Engineering Conference
sponsored by the American Institute of Aeronautics and Astronautics
Providence, Rhode Island, August 16-19, 2004

National Aeronautics and
Space Administration

Glenn Research Center

Acknowledgments

The work described in this paper was performed for the Office of Space Science (Code S), which provides funding for these efforts.

This report contains preliminary findings, subject to revision as analysis proceeds.

Trade names or manufacturers' names are used in this report for identification only. This usage does not constitute an official endorsement, either expressed or implied, by the National Aeronautics and Space Administration.

Available from

NASA Center for Aerospace Information
7121 Standard Drive
Hanover, MD 21076

National Technical Information Service
5285 Port Royal Road
Springfield, VA 22100

Available electronically at <http://gltrs.grc.nasa.gov>

Advanced Radioisotope Power Conversion Technology Research and Development

Wayne A. Wong
National Aeronautics and Space Administration
Glenn Research Center
Cleveland, Ohio, 44135

NASA's Radioisotope Power Conversion Technology program is developing next generation power conversion technologies that will enable future missions that have requirements that cannot be met by either the ubiquitous photovoltaic systems or by current Radioisotope Power System (RPS) technology. Performance goals of advanced radioisotope power systems include improvement over the state-of-practice General Purpose Heat Source/Radioisotope Thermoelectric Generator by providing significantly higher efficiency to reduce the number of radioisotope fuel modules, and increase specific power (watts/kilogram). Other Advanced RPS goals include safety, long-life, reliability, scalability, multi-mission capability, resistance to radiation, and minimal interference with the scientific payload. NASA has awarded ten contracts in the technology areas of Brayton, Stirling, Thermoelectric, and Thermophotovoltaic power conversion including five development contracts that deal with more mature technologies and five research contracts. The Advanced RPS Systems Assessment Team includes members from NASA GRC, JPL, DOE, and Orbital Sciences whose function is to review the technologies being developed under the ten Radioisotope Power Conversion Technology contracts and assess their relevance to NASA's future missions. Presented is an overview of the ten radioisotope power conversion technology contracts and NASA's Advanced RPS Systems Assessment Team.

I. Introduction

NASA has a history of successful space flight missions that depended on radioisotope fueled power systems. These Radioisotope Power Systems (RPS) use the heat generated from the decay of radioisotope material, and convert the heat into useful electrical power. RPS is most attractive in applications where photovoltaics are not optimal such as for deep space applications where the solar flux is too low, or for extended planetary applications such as that on Mars where the day/night cycle, settling of dust, and life requirements limit the usefulness of photovoltaics.

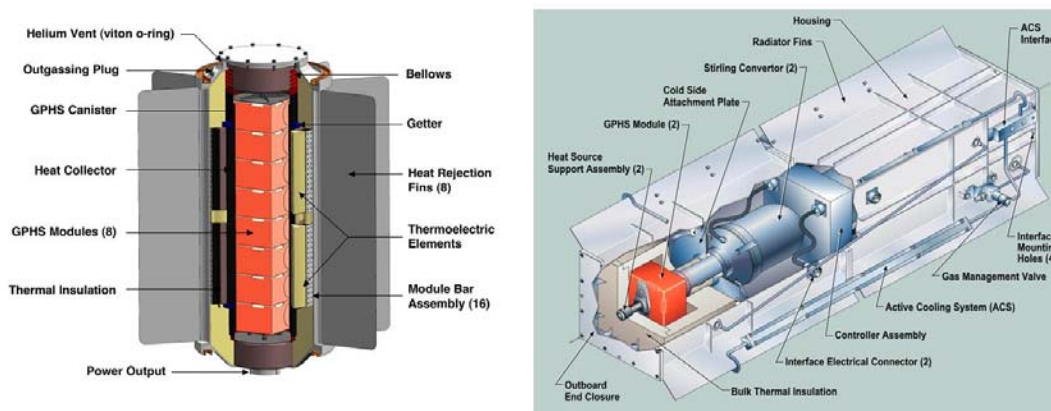


Figure 1.—NASA RPS Flight Development contracts, MMRTG (Left) and SRG (Right) are being managed by The Department of Energy.

Past RPS systems utilized thermoelectrics in the power converters which have proven to be highly reliable, long-lived designs. The U.S. has flown twenty-one space missions that have successfully used Radioisotope Thermoelectric Generators (RTG).¹ The Pioneer 10 spacecraft launched in 1972 utilized four RTGs that continued to provide power to the craft throughout its journey to deep space until the last signal was received 31 years later. The most recent RTG incarnation used on NASA missions incorporate General Purpose Heat Source (GPHS) modules. The GPHS-RTG, which uses Silicon-Germanium Thermoelectric power conversion, was utilized on NASA missions Galileo, Ulysses, and Cassini. The GPHS-RTG uses 18 GPHS modules to provide heat and is designed to generate at least 285 watts electric at Beginning of Mission (BOM). While a proven reliable design, the GPHS-RTG has a relatively low power conversion efficiency of about 7%, a BOM system specific power of about 5 W/kg, and is limited to vacuum environment applications only. Current RPS development efforts are aimed at improving performance, increasing specific power (We/kg), improving scalability, and allowing multi-mission applications, while maintaining reliability for long life.

II. Near Term Technology RPS

The NASA RPS program, recognizing the need for improved RPS, is currently developing two flight systems, the Multi-Mission RTG (MMRTG) and the Stirling Radioisotope Generator (SRG) (Figure 1). Both development efforts are managed by the Department of Energy and the systems are on a development schedule that would have them available for missions starting in 2009. MMRTG is being developed under contract with Boeing-Rocketdyne (Canogapark, CA) and subcontractor Teledyne Energy Systems (Hunt Valley, MD). Power conversion on MMRTG uses Lead-Telluride/Tellurium-Antimony-Germanium-Silver (PbTe/TAGS) thermoelectrics producing about 123 watts (BOM) using 8 GPHS modules.¹ SRG is being developed under contract with Lockheed Martin (Valley Forge, PA) and subcontractor Stirling Technology Company (Kennewick, WA). Power conversion on SRG uses two free-piston Stirling engines coupled to linear alternators producing about 112 watts (BOM) using a total of 2 GPHS modules.^{1,2}

III. Advanced RPS Power Conversion Technology

NASA anticipates future mission requirements that go beyond the capabilities of MMRTG and SRG requiring advanced RPSs that offer better performance and higher specific power. To develop technologies applicable to advanced RPS, NASA released NASA Research Announcement (NRA) 02-OSS-01 entitled "Radioisotope Power Conversion Technology" (RPCT) soliciting proposals for development of next generation power conversion technology. Advanced RPS performance goals include improvement over the State-of-Practice GPHS/RTG including significantly higher efficiency to reduce the number of GPHS modules and higher specific power. Other general Advanced RPS goals include safety, long-life (14 years, with well understood degradation), reliability, scalability, multi-mission capability (vacuum and atmosphere), resistance to radiation (from the GPHS or potential mission environments), and minimal interference with the scientific payload. Of the proposals received in response to the NRA, ten contracts were awarded in the second half of calendar year 2003. The selections include five larger development contracts using more mature technology (Technology Readiness Level (TRL) 3 to 5) and five smaller research contracts using less mature technology (TRL 1 to 3). The selections include a broad range of conversion technologies including dynamic technologies Free-piston Stirling, and Turbo-Brayton, as well as static technologies Thermoelectrics (TE), and Thermophotovoltaics (TPV). While most of the contracts are developing technologies applicable to nominal 100 watt-class RPS, two of the research contracts using thermoelectrics are specific to low power RPS (milli-watt to multi-watt class). Each contract has a period of performance of three years and will be divided into three 1-year phases, with options to continue the following phase after the conclusion of each phase. As of this writing, the 10 RPCT NRA contracts are approaching the conclusion of the first phase. Funding for the first phase of the 10 contracts together total \$13.4 Million.

The emphasis of the RPCT NRA contracts is the development of the power conversion technology (converting heat to electric power). Many auxiliary elements of the RPS are considered to be out of scope of this NRA, such as radiators, GPHS, insulation, etc. and are not included in this technology development effort. It is anticipated that future development efforts in collaboration with DOE will encompass development of the non-converter elements and integration of these components with the power conversion system. The following is a brief summary of the 10 RPCT NRA contracts. As this is the first year of the contract, not all of the contractors have published reports on NRA funded technology development efforts. References 3 to 7 are the reports that have been published to date covering Sunpower's Advanced Stirling Converter development³, Creare's Thermophotovoltaic technology development^{4,5}, and CSU's Stirling Regenerator research^{6,7}.

A. Development Contracts

Five contracts were awarded in the “Development” class defined generally as developing the technology from ~TRL 3 to TRL 5. These development technologies, the prime contractors, and a brief synopsis of the contract goals are as follows:

- 1) Turbo-Brayton: Creare, Inc. (Hanover, NH) has the contract to develop a Turbo Brayton Power System (TBPS) suitable for RPS using Creare’s precision fabrication capabilities for mini-rotor fabrication. The goal is to demonstrate operation of a mini-Turbo Brayton converter that can achieve 25-36% efficiency which Creare estimates if applied in an RPS could result in projected system specific power of 9-13 W/kg. Figure 2 includes photographs of a compressor and a turbine fabricated using Creare’s precision fabrication capability. The Creare team includes Ball Aerospace & Technologies Corp., Boeing-Rocketdyne, and Jackson & Tull. Technical challenges for the team include high temperature turbine and recuperator materials and fabrication.



Figure 2.—Miniature rotors used to demonstrate Creare’s precision fabrication capabilities.

- 2) Free-Piston Stirling: Sunpower, Inc (Athens, OH) is the prime contractor whose goal is to demonstrate an Advanced Stirling Converter with significant improvements over GPHS-RTG, achieving efficiency >30% providing for an estimated RPS specific power >8 W/kg. Figure 3 shows Sunpower’s Frequency Test Bed (FTB) Stirling convertor designed and built within the first 6 months of the contract to allow early high



Figure 3.—Sunpower’s Frequency Test Bed (FTB) Stirling Converter, used to investigate high frequency performance and for advanced component testing.

frequency and advanced component investigations. The Sunpower team consists of Boeing-Rocketdyne, Cleveland State University, University of Minnesota, and consultants Penswick, Gedeon, Berchowitz, and Cairelli. Technical challenges include high temperature materials and fabrication techniques, and providing high efficiency at low power range while maintaining low mass.

- 3) Segmented Thermoelectric: Teledyne Energy Systems (Hunt Valley, MD) is the prime contractor whose goal is to develop a converter with improved performance and manufacturability compared to the Si-Ge thermoelectrics used in the GPHS-RTG by using segmented Bi-Te with PbTe, PbSnTe and TAGS unicouples. The design is based on the Sentinel units developed for terrestrial applications. Teledyne's goal is to demonstrate 10% conversion efficiency by using improved materials providing >5 W/kg system specific power. A single compact module is matched to a single GPHS allowing for higher power levels by using multiple modules and GPHSs. The Phase 1 module is expected to produce 20 We with potential improvements in later phases. Figure 4 illustrates Teledyne's concept for a single compact module. Boeing-Rocketdyne is a subcontractor on this Teledyne contract. Technical challenges include developing processing techniques that provide improved performance materials, and prevention of TAGS sublimation.

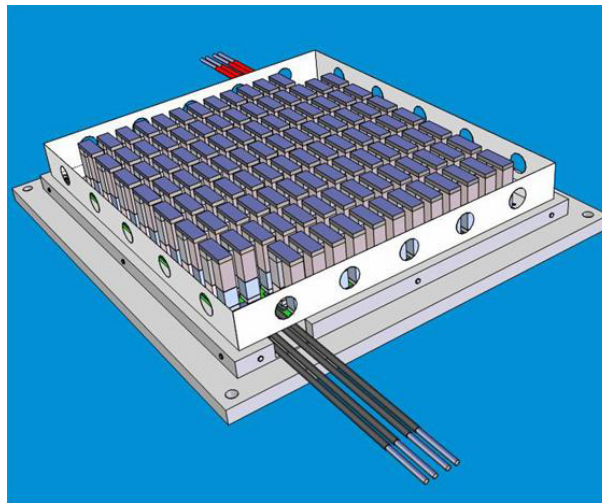


Figure 4.—Teledyne Energy Systems concept for a compact module using segmented thermoelectrics.

- 4) Thermophotovoltaic: Creare, Inc. (Hanover, NH) is the prime contractor and the goal is to demonstrate a TPV power converter using selective emitters, spectral control filters, and InGaAs cells. The performance

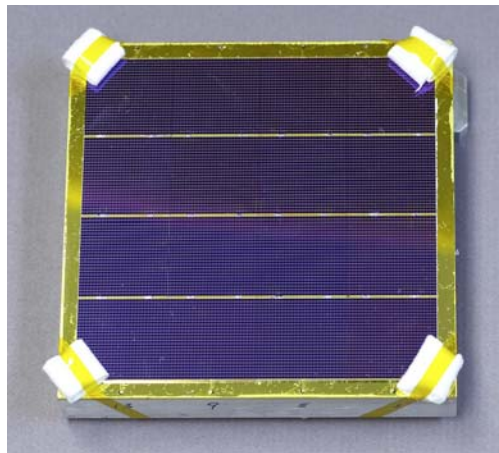


Figure 5.—4"x4" TPV array produced under the Creare contract.

target is to provide 15-20% converter efficiency, which Creare estimates will enable an RPS with a system specific power of ~15 W/kg. Figure 5 is a photo of a 4"x4" MIM array produced during Phase I. The Creare team consists of Emcore Corp., NASA GRC, Polytechnic University, and Oak Ridge National Laboratory. Technical challenges for the team include optical and thermal performance optimization, spectral control filter fabrication, performance degradation due to exposure to radiation, and material evaporation and deposition.

- 5) Thermophotovoltaic: Edtek, Inc. (Kent, WA) is the prime contractor whose goal is to demonstrate a TPV power converter employing improvements in GaSb photovoltaic cell technology, an IR filter housing, and thermal isolation of the PV array. Performance goal is to achieve 17-23% converter efficiency, which is estimated to provide an RPS specific power of >8 W/kg. Figure 6 is a photo of Edtek's TPV cell array and prism array. Three of these arrays make up a 4"x4" unit. Edtek is collaborating with subcontractor the University of Houston on this contract. Technical challenges include the development of enhanced emitter surfaces that are stable with time at high temperature, high throughput multi-layer filters, component optimization, and performance degradation due to exposure to radiation.

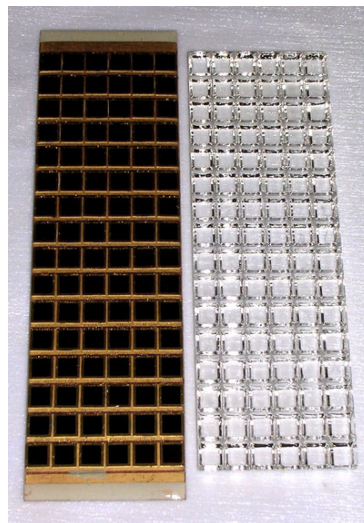


Figure 6.—One of Edtek's prism arrays (right) used to concentrate energy onto the cells of the TPV array (left).

B. Research Contracts

Five NRA contracts were awarded in the "Research" class defined as TRL ≤ 3 . These research technologies, the contractors, and a brief synopsis of the contract goals are as follows:

- 1) Stirling: Cleveland State University (Cleveland, OH) is the prime contractor whose goal is to develop micro-fabrication techniques for Stirling regenerators that would lead to improved thermal and flow performance of this heat exchanger, and then to characterize these performance enhancements in an engine. Projections indicate that performance improvement up to ~9% higher power may be possible. The CSU team includes University of Minnesota, Gedeon Associates, Sunpower, Stirling Technology Company, and Mezzo Systems. Technical challenges include the selection of appropriate geometry for enhancing regenerator performance, selection of an appropriate fabrication technique, and establish reliability of concept.
- 2) Thermoelectric milli-watt/multi-watt class systems: Teledyne Energy Systems (Hunt Valley, MD) is also the prime contractor on this effort to develop cascaded PbTe/TAGS-superlattice BiTe TE technology for milli-watt RPS applications. The performance goal is to demonstrate module efficiencies $\geq 8\%$ with power

output of 50 to several 100 mW. The design is for a glass-bonded, close-packed monolithic device. Research Triangle Institute is the subcontractor to Teledyne on this contract. Technical challenges include the development and fabrication of a close-packed cascaded monolithic device using TE elements with large length-to-area ratio.

- 3) Thermoelectric milli-watt/multi-watt class systems: Hi-Z Technology Inc (San Diego, CA) is the prime contractor and is developing Quantum Well (QW) materials for use in high temperature multicouple applications. Hi-Z's goal is to demonstrate multicouple efficiencies of 25-40%, fabricating the device by sputtering multi-layer QW films. Technical challenges include demonstrating improved material characteristics (ZT), and demonstrating couple efficiency.
- 4) Thermoelectric: Massachusetts Institute of Technology (Cambridge, MA) is the prime contractor whose goal is to utilize nano-structure technology to improve ZT in Si-Ge bulk materials. The goal is to demonstrate ZT of ~2 at 900K with efficiency of 12-14% and then to develop a mass production method to fabricate devices using this material. The technique uses vapor condensation of Si-Ge nano-wires. MIT is teamed with the Jet Propulsion Laboratory and Boston College on this contract. Technical Challenges include decreasing thermal conductivity, while maintaining or increasing electronic transport.
- 5) Thermophotovoltaic: Essential Research Inc., (Cleveland, OH) is the prime contractor whose goal is to grow and characterize 0.74eV and then 0.6eV InGaAs-on-InP dot-junction photovoltaic cells and to demonstrate 30% conversion efficiency. Essential Research is teamed with Ohio Aerospace Institute, and the University of Notre Dame on this contract. Technical challenges include micro scale fabrication of TPV cells and lattice mismatched cell fabrication.

IV. Systems Assessment Team

The Advanced RPS Systems Assessment Team (SAT) is a government led team composed of members from NASA Glenn Research Center (lead), Jet Propulsion Laboratory, Department of Energy and Orbital Sciences Corporation.

The SAT's primary roles are to:

- Assess the technologies being developed under the 10 RPCT NRA contracts
- Evaluate the performance of the contractors
- Provide recommendations to the RPS Program with regard to status of the technology, technology development options, phase-to-phase funding, and potential down-selection.

Secondary roles for the SAT are to:

- Evaluate technologies against mission requirements
- Develop conceptual designs & project system level performance
- Provide data on Advanced RPS systems to mission planners

The SAT reviews contractor monthly and Final Reports along with design and test reports, and participates in contract mid-year and end-of-year reviews in order to keep abreast of technical progress on the contracts. The SAT will also develop conceptual designs of RPS using the power conversion technologies being developed under these NRA contracts. Using the Decadel Surveys⁸ as a starting point, the team will identify missions where advanced RPS may be enabling, and then identify the mission requirements. The team will perform system trade studies and system comparison studies in order to assess the system level benefits of the power conversion technologies. Other activities for the SAT include performance and life Validation & Verification modeling and testing on materials, components, and devices developed under the NRA contracts as required. Long range planning also assumes that at the conclusion of Phase III, multiple devices will be delivered to NASA for evaluation testing.

The contractors will be evaluated in the following areas: technical progress, merits of proposed technology, performance of contractor, relevance of technology to NASA goals, and plans for Phase II and III.

V. Conclusion

NASA has used radioisotope fuel to power numerous past missions successfully. Radioisotope Power Systems have proven very effective in applications where PV arrays are not practical. Two flight system development efforts currently underway are the MMRTG and the SRG to support NASA near term mission requirements. Next generation RPS, with higher efficiency, higher specific power (W/kg), long life, high reliability, scalability, and multi-mission capability are also being developed under 10 contracts awarded under the Radioisotope Power Conversion Technology NRA. These contracts, five larger contracts for higher TRL Development efforts, and five smaller contracts for lower TRL Research efforts, are in the technology areas of Turbo-Brayton, Free-Piston Stirling, Thermoelectrics, and Thermophotovoltaics. These contracts are nearing the completion of the first year of funding as of this writing. An Advanced RPS Systems Assessment Team has been formed to review the work of the RPCT contractors, to assess the relevance of the technologies to NASA's future needs, and to provide recommendations to the RPS program.

References

¹Solar System Exploration Division, Office of Space Science, NASA Headquarters, "NASA's Program for Radioisotope Power System Research and Development," Proceedings of the 2nd International Energy Conversion Engineering Conference (IECEC 2004), Providence, RI, August 16-19, 2004

²Cockfield, R. D. and Chan, T. S., "Stirling Radioisotope Generator for Mars Surface and Deep Space Missions," Proceedings of the 37th Intersociety Energy Conversion Engineering Conference, Washington, D.C., IECEC 2002 Paper No. 20188, 2002.

³Wood, J. G. and Carroll, C., "Advanced Stirling Converter Program Update," Proceedings of the 2nd International Energy Conversion Engineering Conference (IECEC 2004), Providence, RI, August 16-19, 2004

⁴Crowley, C.J., Murray, S., Murray, C.S., and Elkouh, N.A., "Thermophotovoltaic Converter Design for Radioisotope Power Systems," Space Technology and Applications International Forum (STAIF 2004), Albuquerque, NM, February 8-11, 2004.

⁵Murray, C.S., Crowley, C.J., Murray, S., Elkouh, N.A., Hill, R.W. and Chubb, D.E., "Thermophotovoltaic Converter Design for Radioisotope Power Systems," 6th NREL Conference on Thermophotovoltaic Generation of Electricity, Freiburg, Germany, June 14-16, 2004.

⁶Sun, L., Mantell, S., Gedeon, D., Simon, T., "A Survey of Microfabrication Techniques for Use in Stirling Engine Regenerators," AIAA-2004-5647, Proceedings of the 2nd International Energy Conversion Engineering Conference (IECEC 2004), Providence, RI, August 16-19, 2004.

⁷Ibrahim, M. B., Veluri, S., Simon, T., Gedeon, D., "CFD Modeling of Surface Roughness in Laminar Flow," AIAA-2004-5585, Proceedings of the 2nd International Energy Conversion Engineering Conference (IECEC 2004), Providence, RI, August 16-19, 2004.

⁸"New Frontiers in the Solar System – An Integrated Exploration Strategy," National Research Council of the National Academies, 2003.

REPORT DOCUMENTATION PAGE			Form Approved OMB No. 0704-0188	
Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188), Washington, DC 20503.				
1. AGENCY USE ONLY (Leave blank)		2. REPORT DATE December 2004		3. REPORT TYPE AND DATES COVERED Technical Memorandum
4. TITLE AND SUBTITLE Advanced Radioisotope Power Conversion Technology Research and Development			5. FUNDING NUMBERS WBS-22-972-30-03	
6. AUTHOR(S) Wayne A. Wong				
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) National Aeronautics and Space Administration John H. Glenn Research Center at Lewis Field Cleveland, Ohio 44135-3191			8. PERFORMING ORGANIZATION REPORT NUMBER E-14820	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) National Aeronautics and Space Administration Washington, DC 20546-0001			10. SPONSORING/MONITORING AGENCY REPORT NUMBER NASA TM-2004-213352 AIAA-2004-5515	
11. SUPPLEMENTARY NOTES Prepared for the Second International Energy Conversion Engineering Conference sponsored by the American Institute of Aeronautics and Astronautics, Providence, Rhode Island, August 16-19, 2004. Responsible person, Wayne A. Wong, organization code 5490, 216-433-6318.				
12a. DISTRIBUTION/AVAILABILITY STATEMENT Unclassified - Unlimited Subject Category: 20 Available electronically at http://gltrs.grc.nasa.gov This publication is available from the NASA Center for AeroSpace Information, 301-621-0390.			12b. DISTRIBUTION CODE	
13. ABSTRACT (Maximum 200 words) NASA's Radioisotope Power Conversion Technology program is developing next generation power conversion technologies that will enable future missions that have requirements that cannot be met by either the ubiquitous photovoltaic systems or by current Radioisotope Power System (RPS) technology. Performance goals of advanced radioisotope power systems include improvement over the state-of-practice General Purpose Heat Source/Radioisotope Thermoelectric Generator by providing significantly higher efficiency to reduce the number of radioisotope fuel modules, and increase specific power (watts/kilogram). Other Advanced RPS goals include safety, long-life, reliability, scalability, multi-mission capability, resistance to radiation, and minimal interference with the scientific payload. NASA has awarded ten contracts in the technology areas of Brayton, Stirling, Thermoelectric, and Thermophotovoltaic power conversion including five development contracts that deal with more mature technologies and five research contracts. The Advanced RPS Systems Assessment Team includes members from NASA GRC, JPL, DOE and Orbital Sciences whose function is to review the technologies being developed under the ten Radioisotope Power Conversion Technology contracts and assess their relevance to NASA's future missions. Presented is an overview of the ten radioisotope power conversion technology contracts and NASA's Advanced RPS Systems Assessment Team.				
14. SUBJECT TERMS RPS; Radioisotope power systems; Brayton; Stirling; Thermoelectric; Thermophotovoltaic			15. NUMBER OF PAGES 13	
			16. PRICE CODE	
17. SECURITY CLASSIFICATION OF REPORT Unclassified	18. SECURITY CLASSIFICATION OF THIS PAGE Unclassified	19. SECURITY CLASSIFICATION OF ABSTRACT Unclassified	20. LIMITATION OF ABSTRACT	

